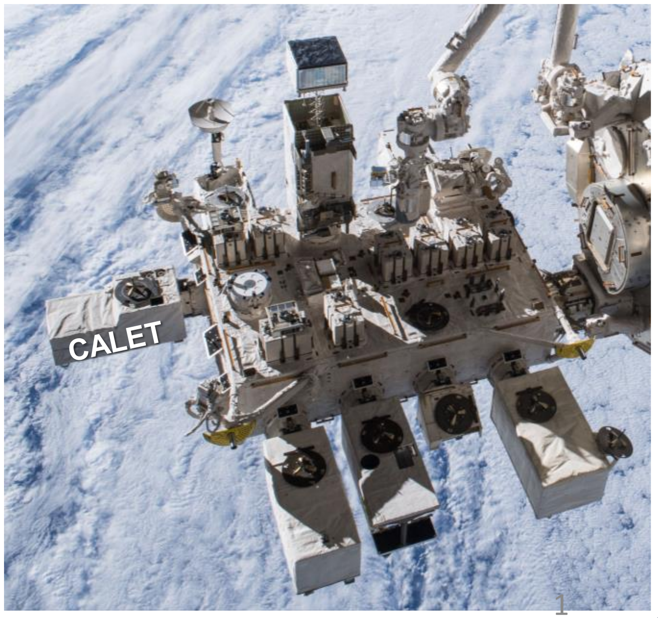
CALET Results After Three Years on the International Space Station

Yoichi Asaoka
for the CALET collaboration
WISE, Waseda University



XVI International Conference on Topics in Astroparticle and Underground Physics

TAUP 2019 TOYAMA

The biennial TAUP series covers recent experimental and theoretical developments in astroparticle physics including Cosmology and particle physics, Dark matter and dark energy, Neutrino physics and astrophysics, Gravitational waves, High-energy astrophysics and cosmic rays

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Toyama International Conference Center, Toyama, Japan

CALET Collaboration Team

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Direct measurements of cosmic rays : little room for "unknown" systematics

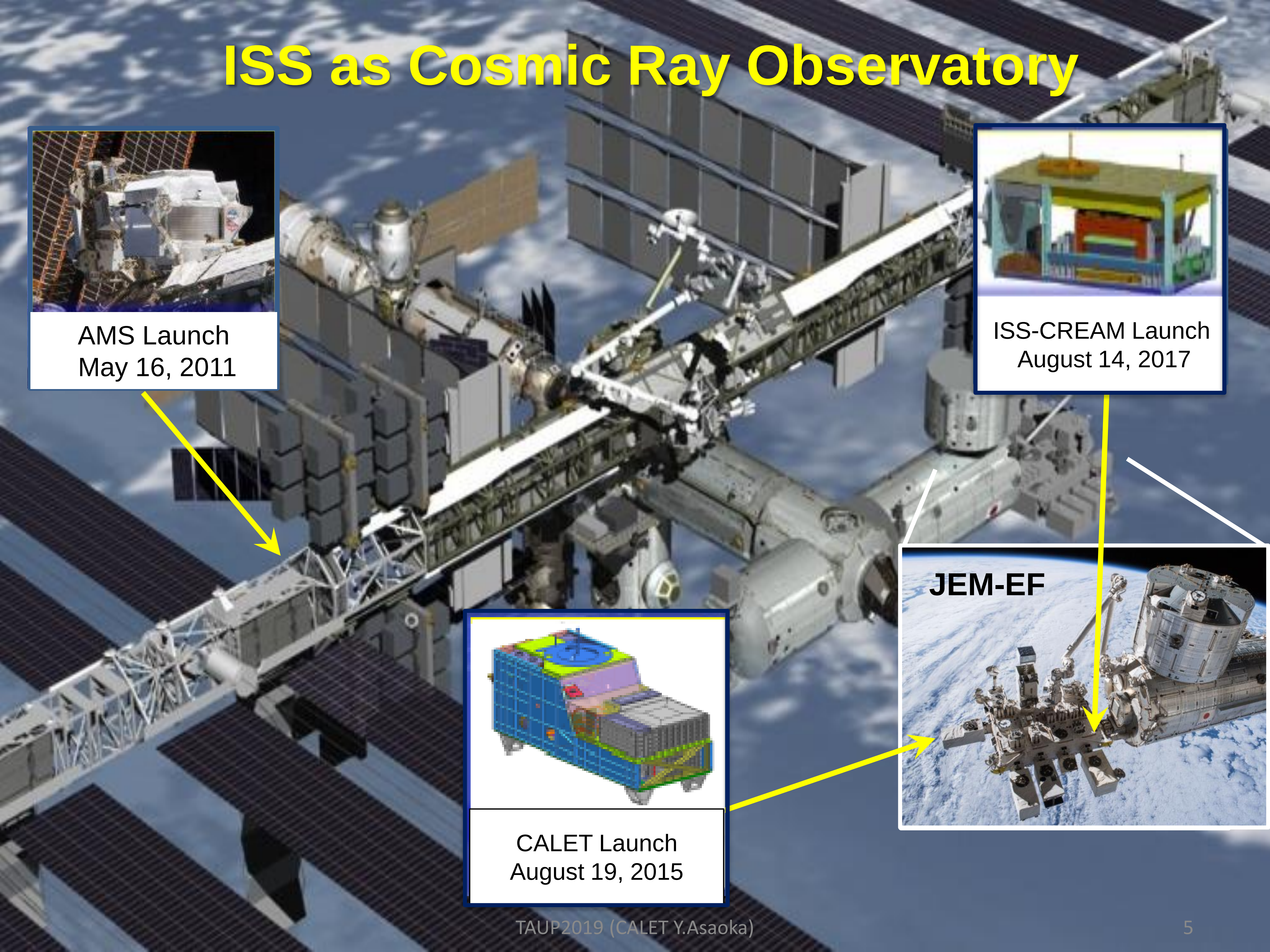
Four major factors in the spectrum measurements:

1. Acceptance $\Rightarrow$ **$S\Omega$**
   - Geometrical Factor
2. Energy determination $\Rightarrow$ **$\Delta E/E$ (resolution)**
   Energy Scale
   Typically:
   - Magnet spectrometer
   - Calorimeter
3. Particle identification $\Rightarrow$ **r_{BG} (contamination ratio)**
   - Rejection of background cosmic rays
4. Detection efficiency $\Rightarrow$ **ε**
   - Losses in the detector

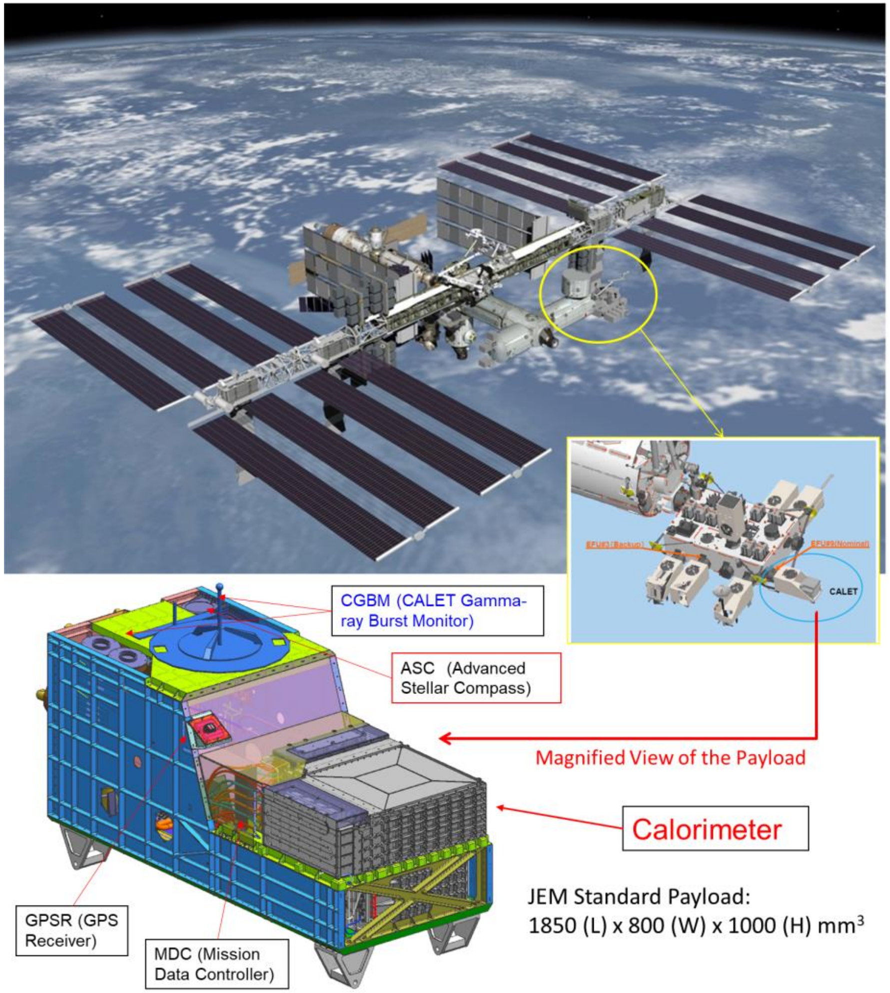
Question: How "direct" each measurement is?

Larger corrections leave more rooms for "unknown" systematics

ISS as Cosmic Ray Observatory



CALET: Cosmic Ray Detector onboard the ISS



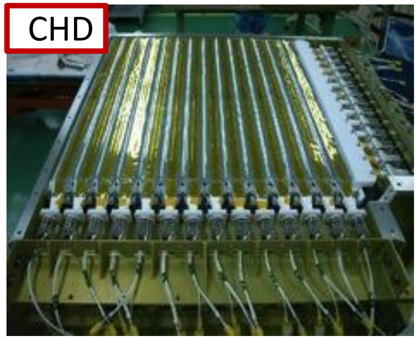
Continues stable observation since Oct. 13, 2015 and collected ~1.8 billion events so far.

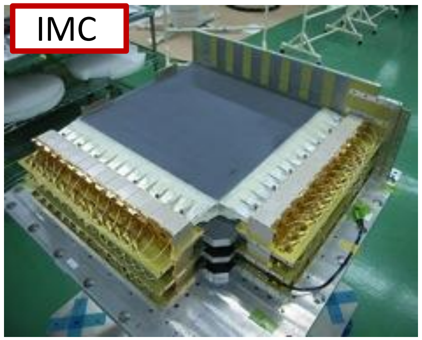
Overview of CALET Observations

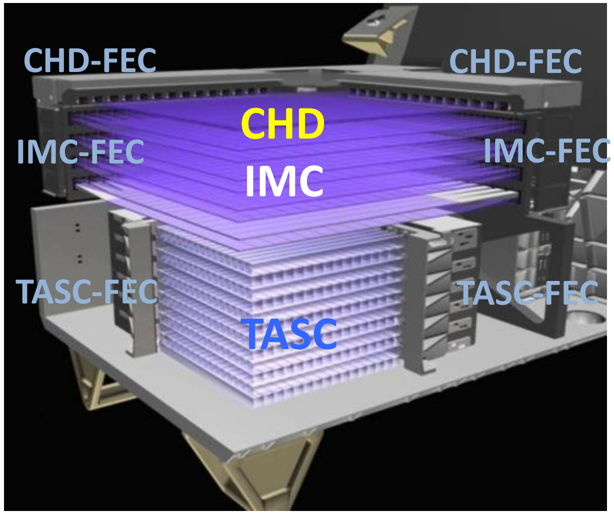
- Direct cosmic ray observations in space at the highest energy region by combining:
  - ✓ A large-size detector
  - ✓ Long-term observation onboard the ISS (5 years or more is expected)
- Electron observation in the 1 GeV - 20 TeV energy range, with high energy resolution owing to optimization for electron detection
  ⇨ Search for Dark Matter and Nearby Sources
- Observation of cosmic-ray nuclei in the 10 GeV - 1 PeV energy range.
  ⇨ Unravelling the CR acceleration and propagation mechanism
- Detection of transients in space by long-term stable observations
  ⇨ EM radiation from GW sources, Gamma-ray burst, Solar flare, etc.

CALET Instrument

CALORIMETER



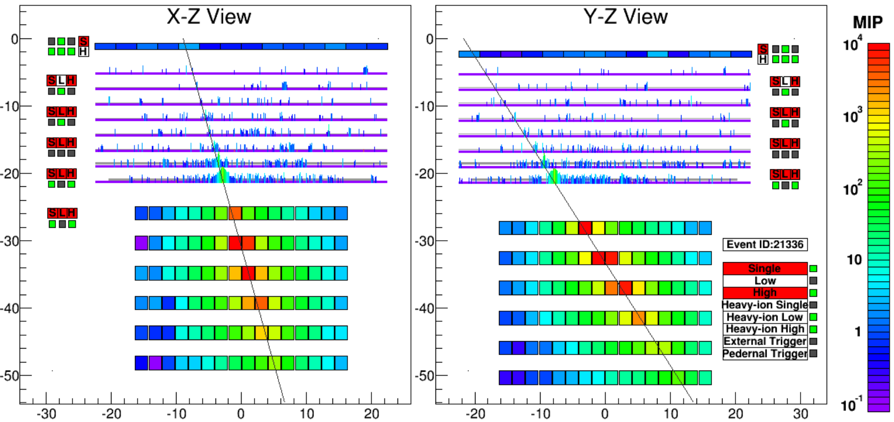




	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers ($3X_0$): $0.2X_0$ x 5 + $1X_0$ x2 Scifi size : 1 x 1 x 448 mm^3**	**16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm^3 Total Thickness : 27 X_0 , ~1.2 λ_I**
Readout	**PMT+CSA**	**64-anode PMT+ ASIC**	**APD/PD+CSA PMT+CSA (for Trigger)@top layer**

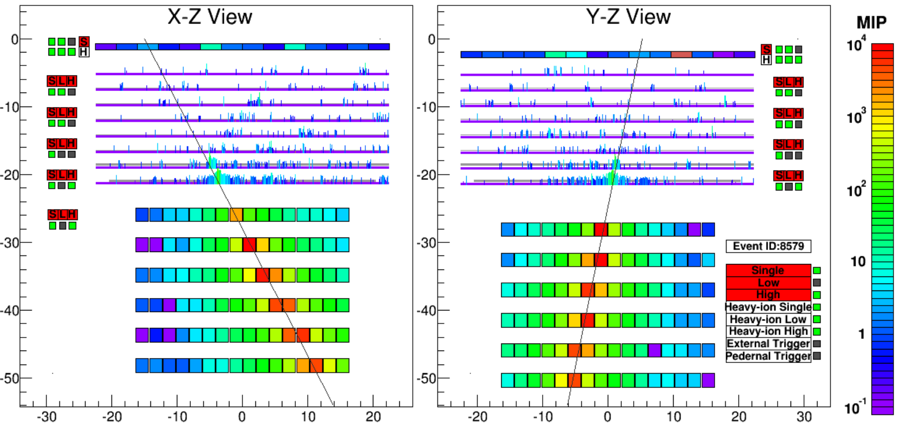
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



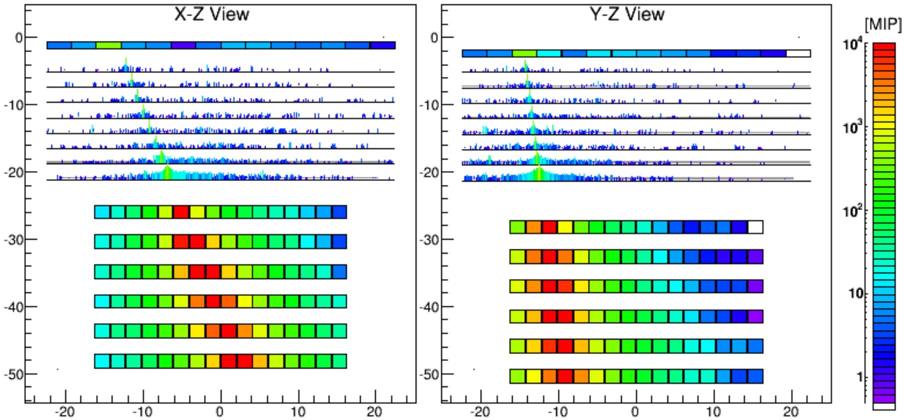
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



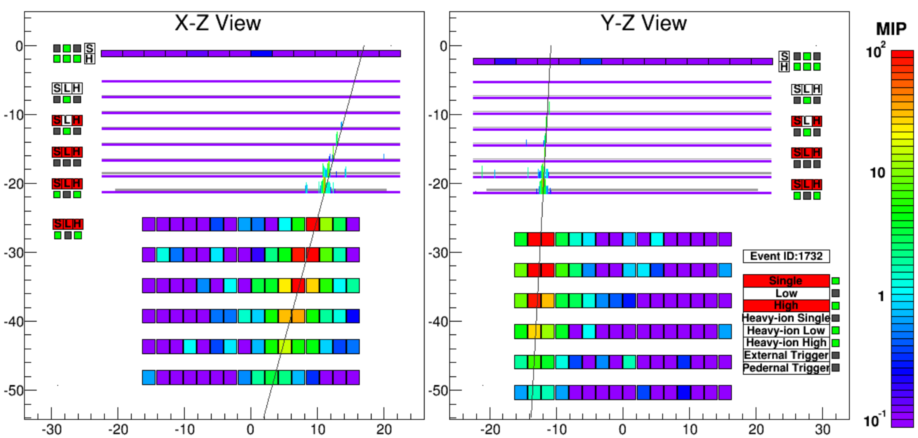
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

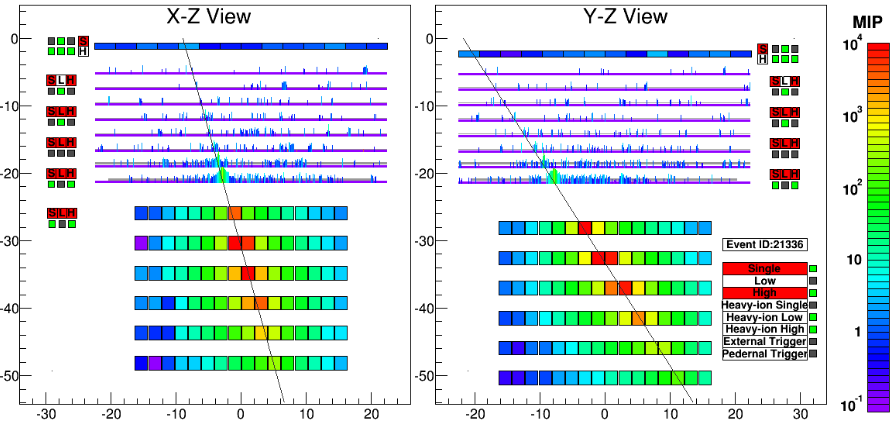
Gamma-ray, E=44.3 GeV



no energy deposit before pair production

Event Examples of High-Energy Showers

Electron, E=3.05 TeV



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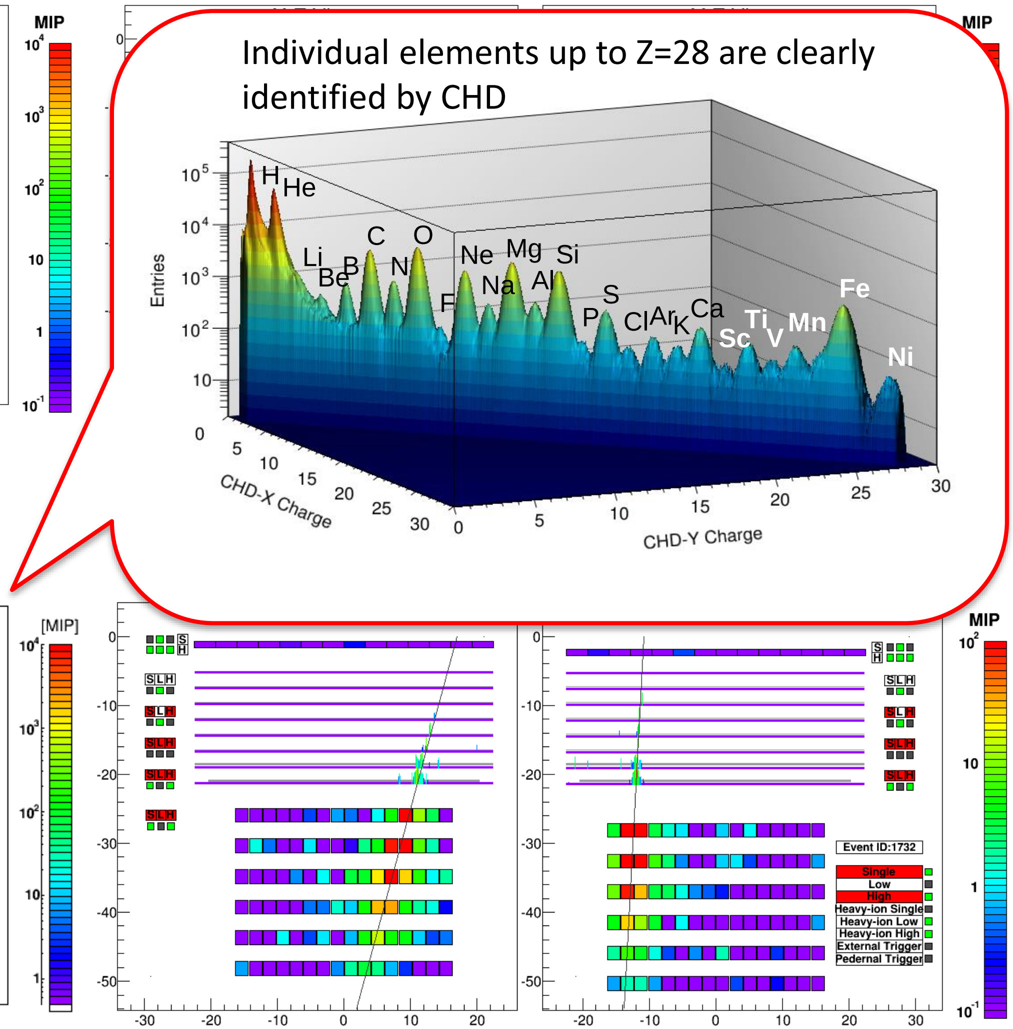
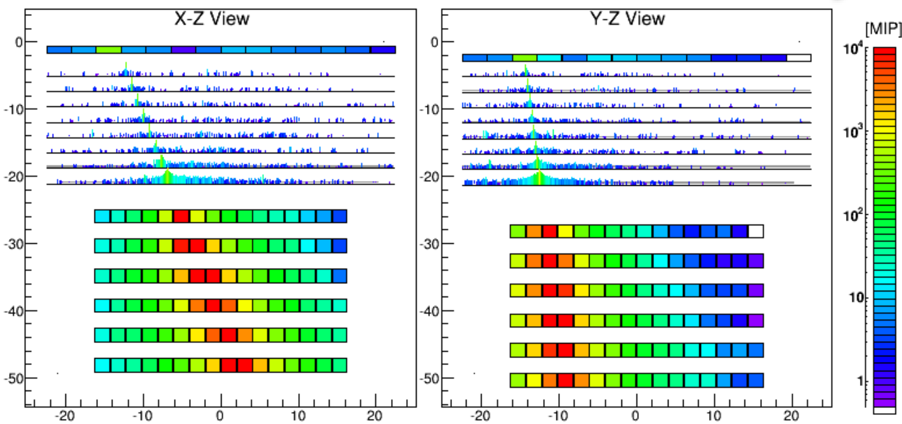
Proton, ΔE=2.89 TeV



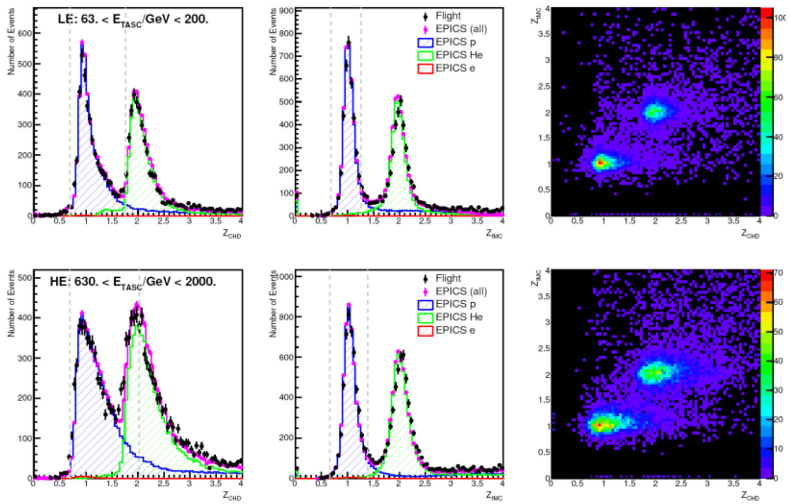
Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

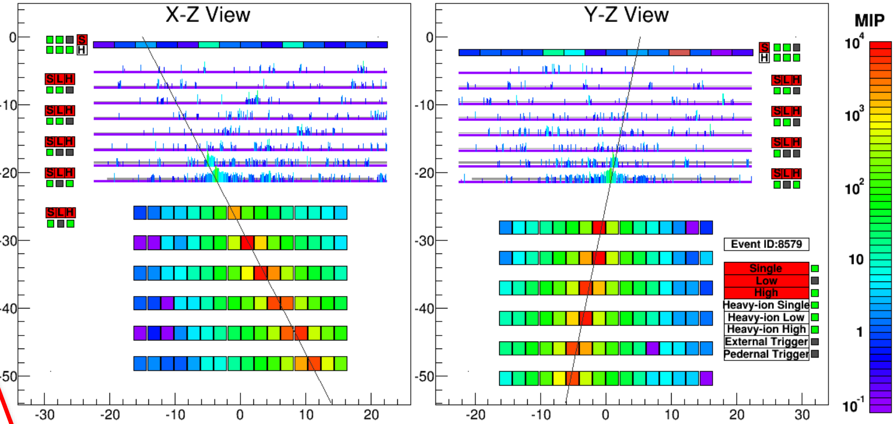
no energy deposit before pair production

Event Examples of High-Energy Showers



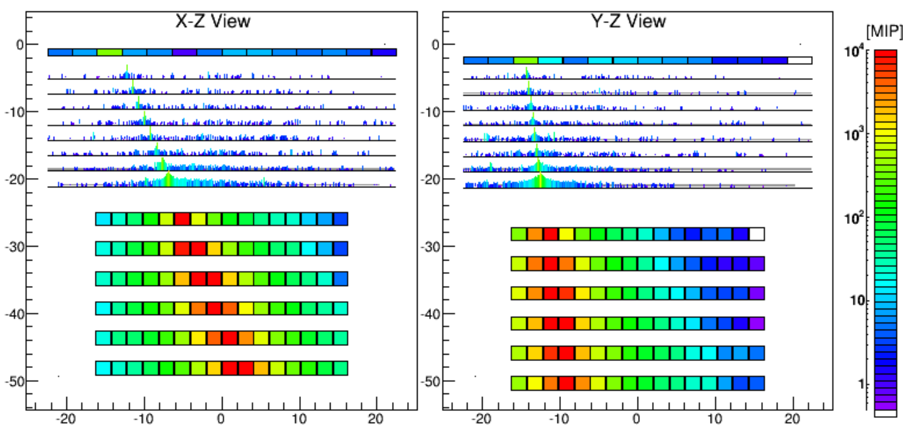
Proton/helium separation using CHD/IMC charge

Proton, ΔE=2.89 TeV



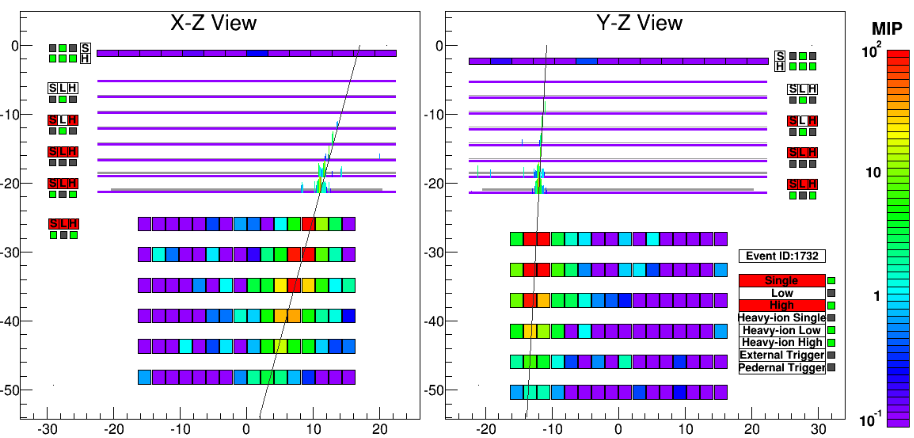
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

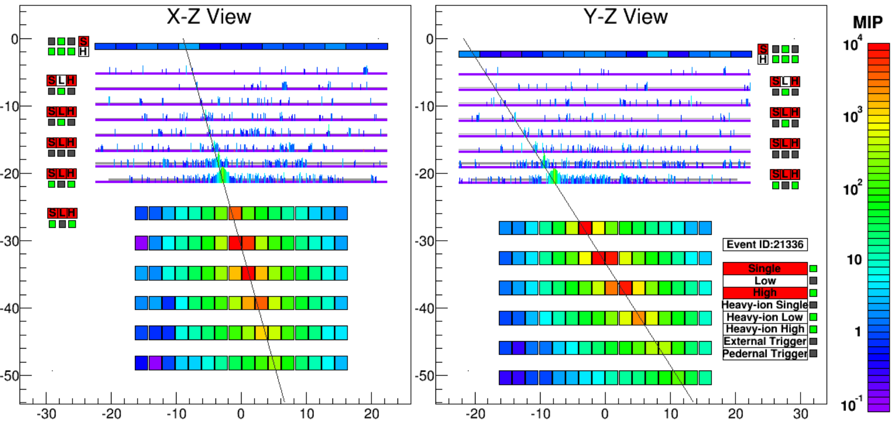
Gamma-ray, E=44.3 GeV



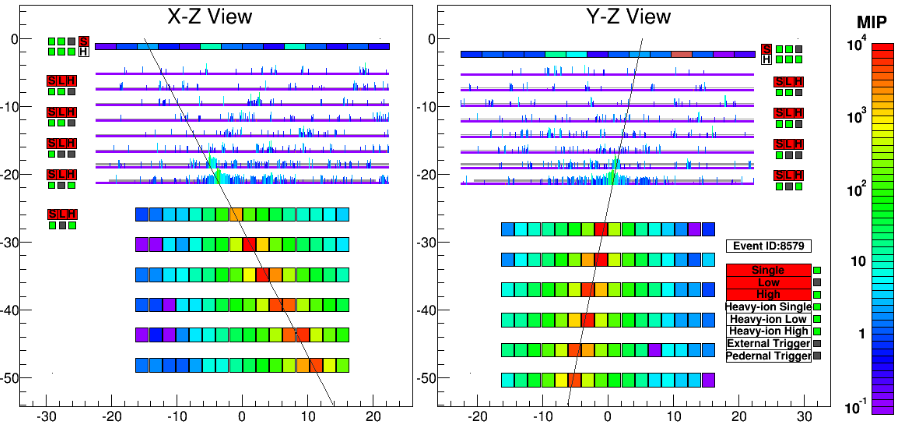
no energy deposit before pair production

Event Examples of High-Energy Showers

Electron, E=3.05 TeV



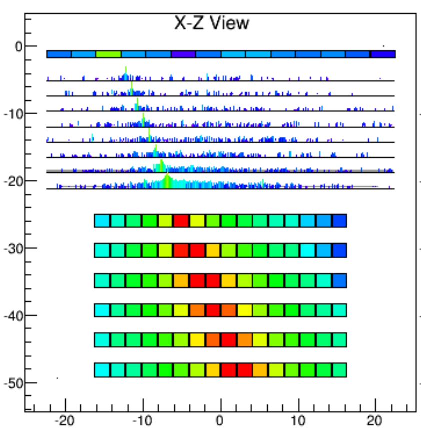
Proton, ΔE=2.89 TeV

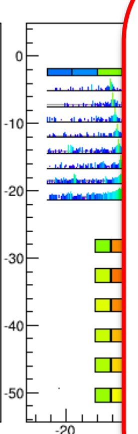


fully contained even at 3TeV

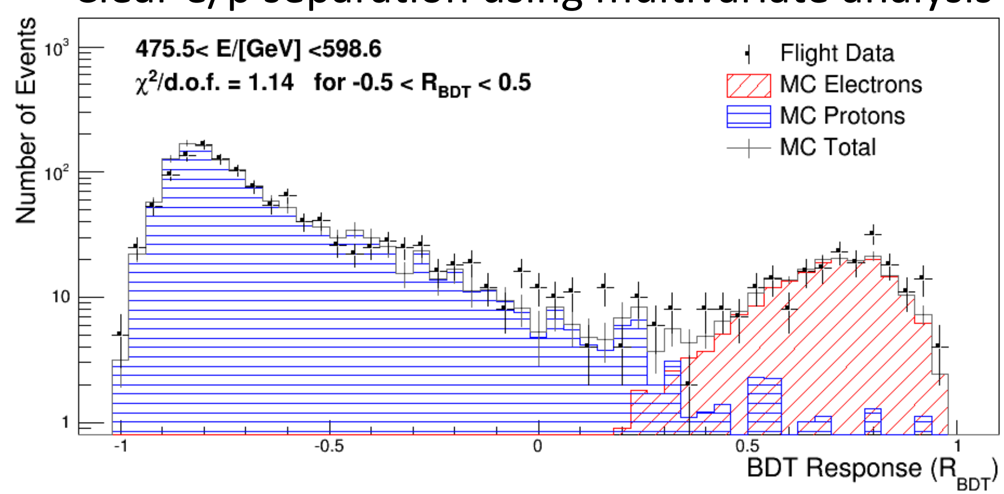
clear difference from electron shower

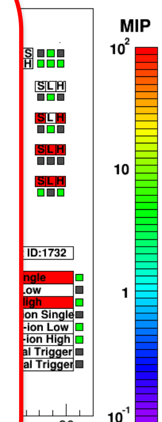
Fe(Z=26), ΔE=9.





Clear e/p separation using multivariate analysis



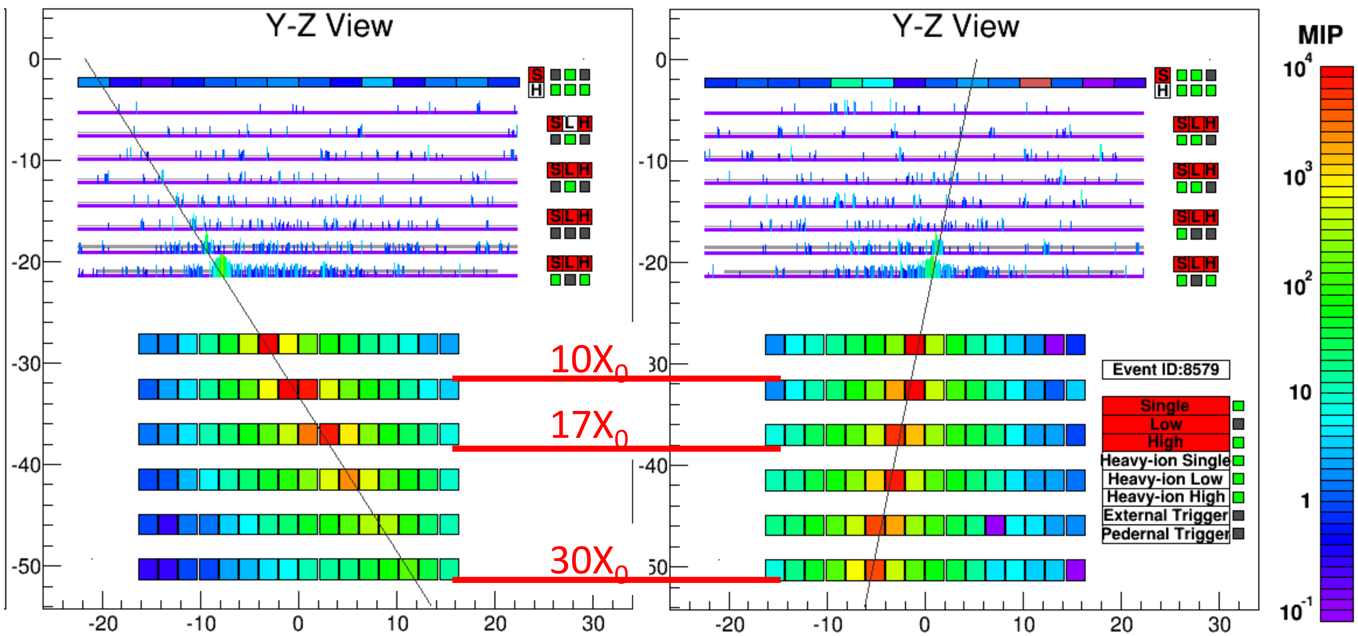


energy deposit in CHD cons ... ction

All-Electron Measurement with CALET

3TeV Electron Candidate

Corresponding Proton Background



(Flight data; detector size in cm)

1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   $30X_0$ thickness, closely packed logs

⇒ CALET is best suited for observation of possible fine structures in the all-electron spectrum up to the trans-TeV region.

All-Electron Measurement with CALET: room for "unknown" systematics

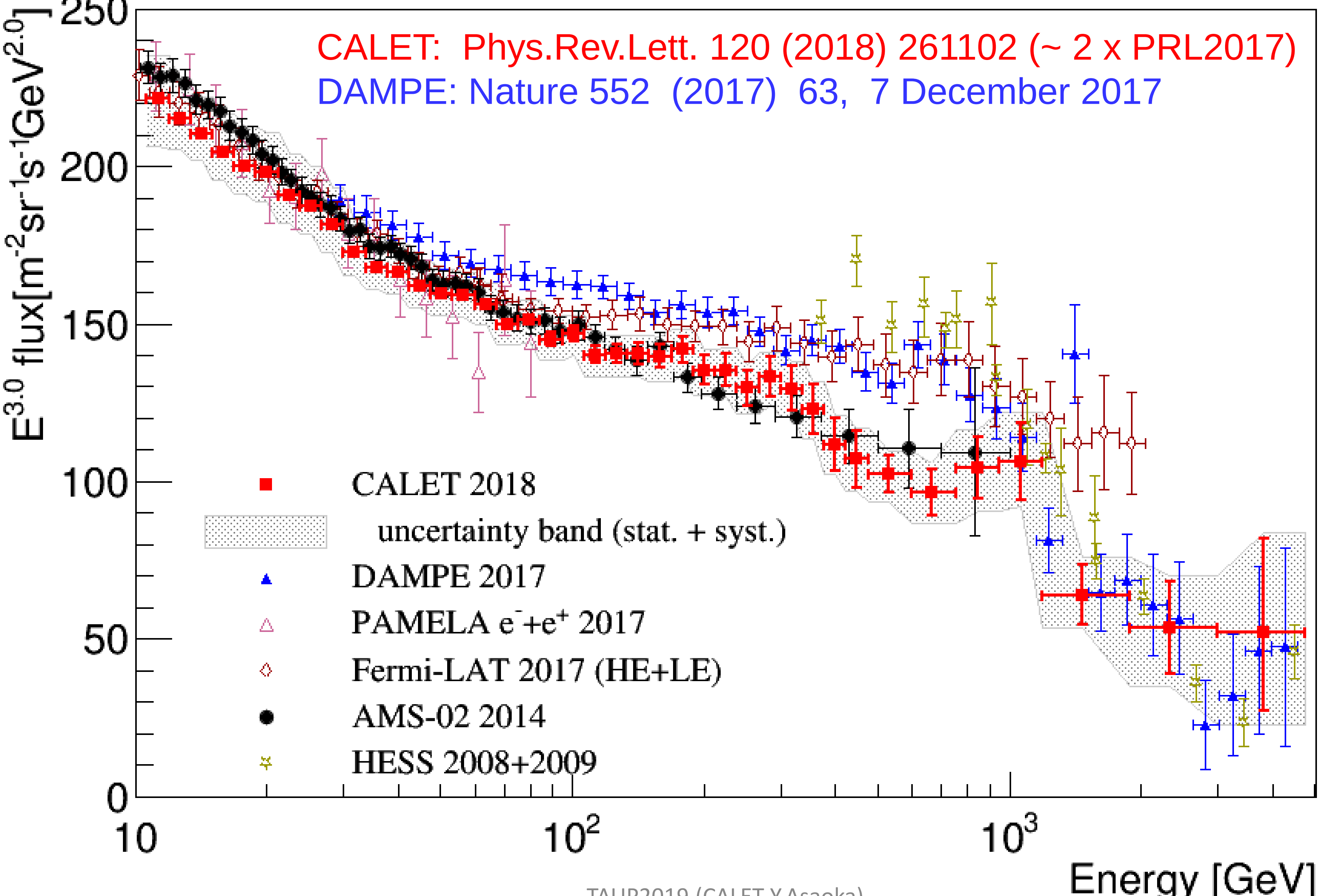
1. Acceptance ⇒ **well defined SΩ because of reliable tracking**
   - Geometrical factor
2. Energy determination ⇒ **$\Delta E/E$ ~ 2% (E>20GeV) absolute energy scale calibrated by geomagnetic rigidity cutoff**
   - Magnet Spectrometer
   - **Calorimeter**
3. Particle identification ⇒ **r_{BG} < 5% (E<1TeV) r_{BG} ~ 10—20% (1<E<5TeV)**
   - Contamination
4. Detection efficiency ⇒ **ε > 70% (E>30GeV) keeps constant value**
   - Losses in the detector

⇒ **<u>Leaves little room</u> for "unknown" systematics**

combined with detailed systematic studies (see PRLs + SM)

All Electron Spectrum: Extended Measurement by CALET

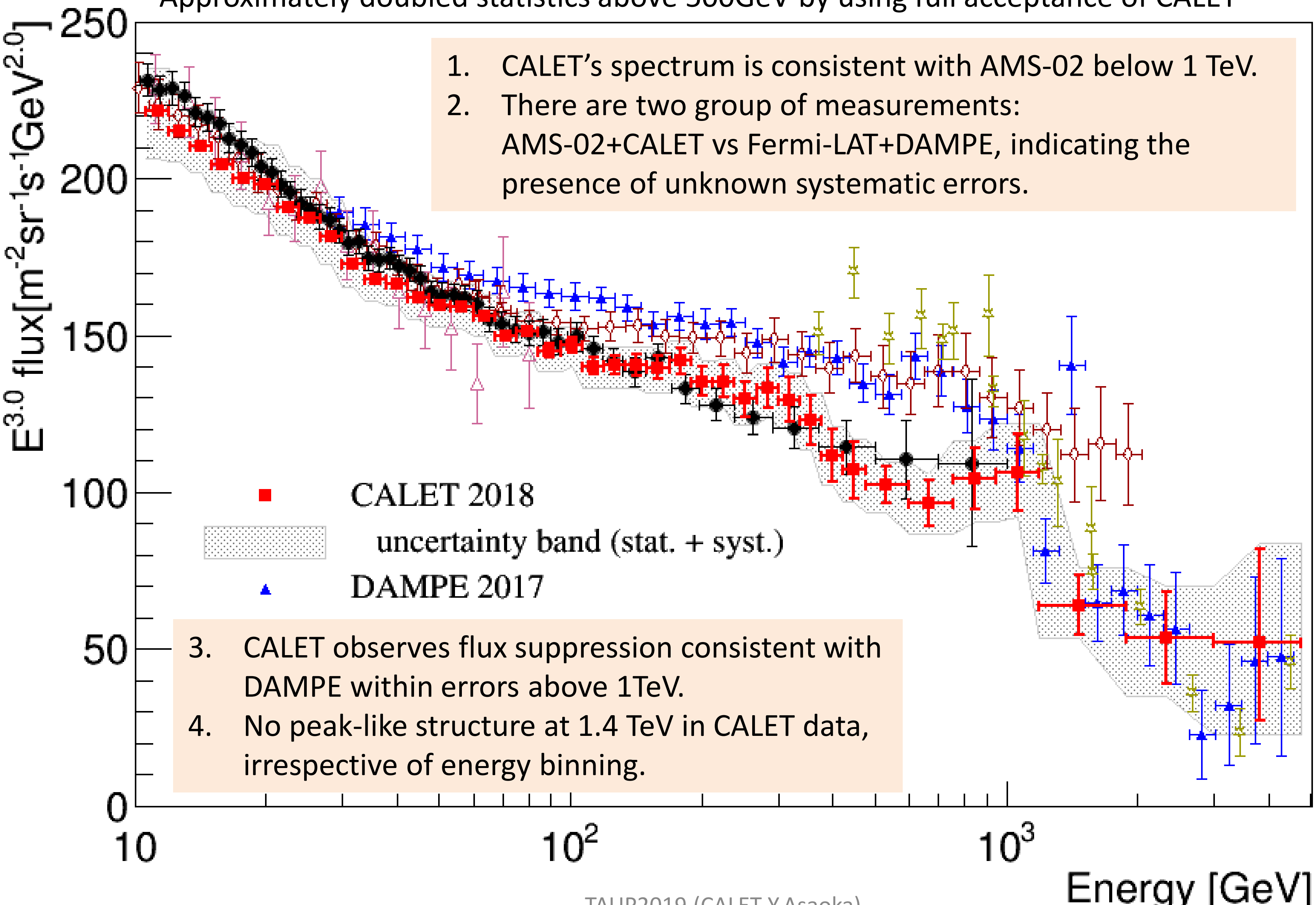
Approximately doubled statistics above 500GeV by using full acceptance of CALET



All Electron Spectrum: Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET

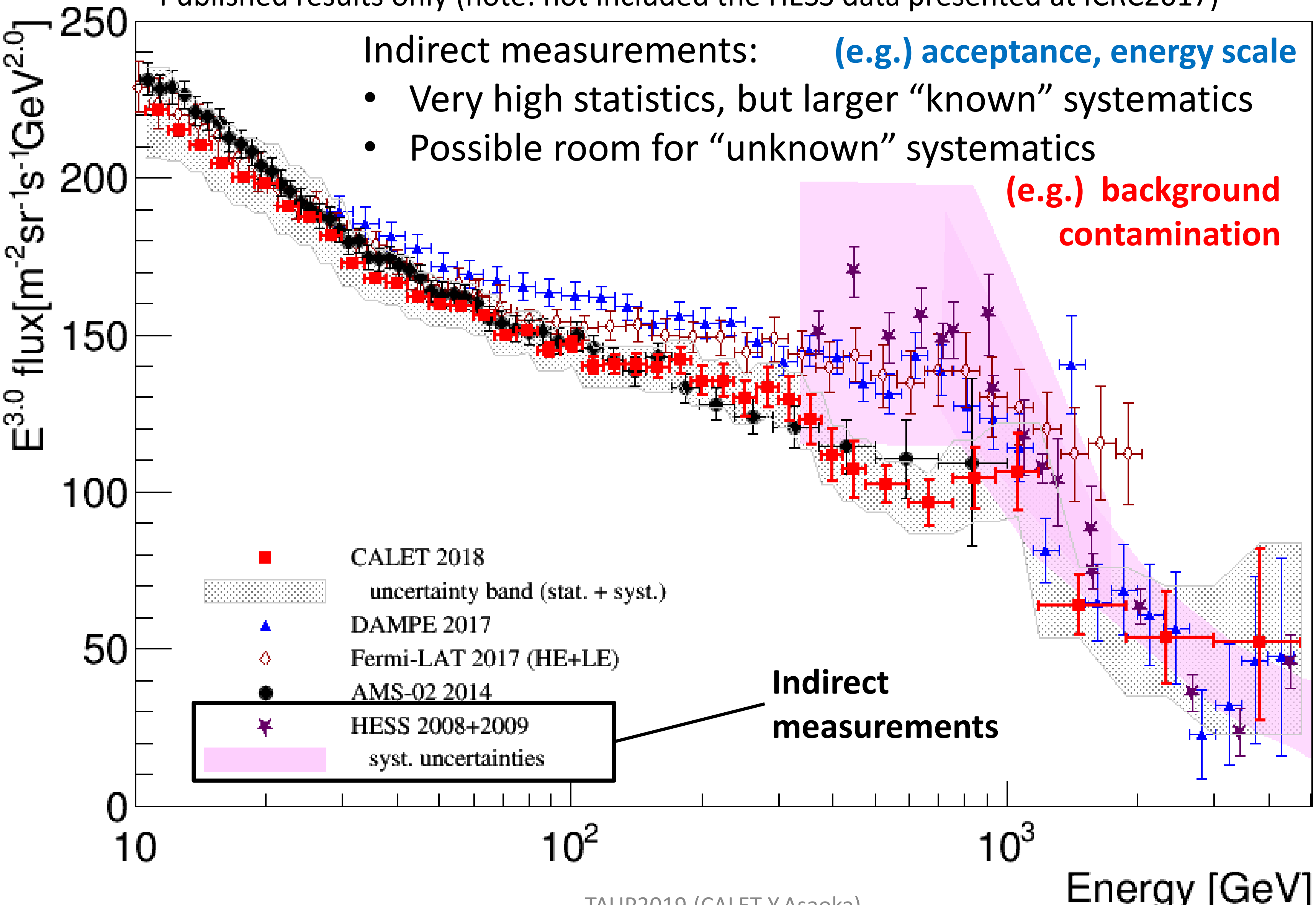
1. CALET's spectrum is consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.



3. CALET observes flux suppression consistent with DAMPE within errors above 1TeV.
4. No peak-like structure at 1.4 TeV in CALET data, irrespective of energy binning.

All Electron Spectrum: Comparison with Indirect Measurements

Published results only (note: not included the HESS data presented at ICRC2017)



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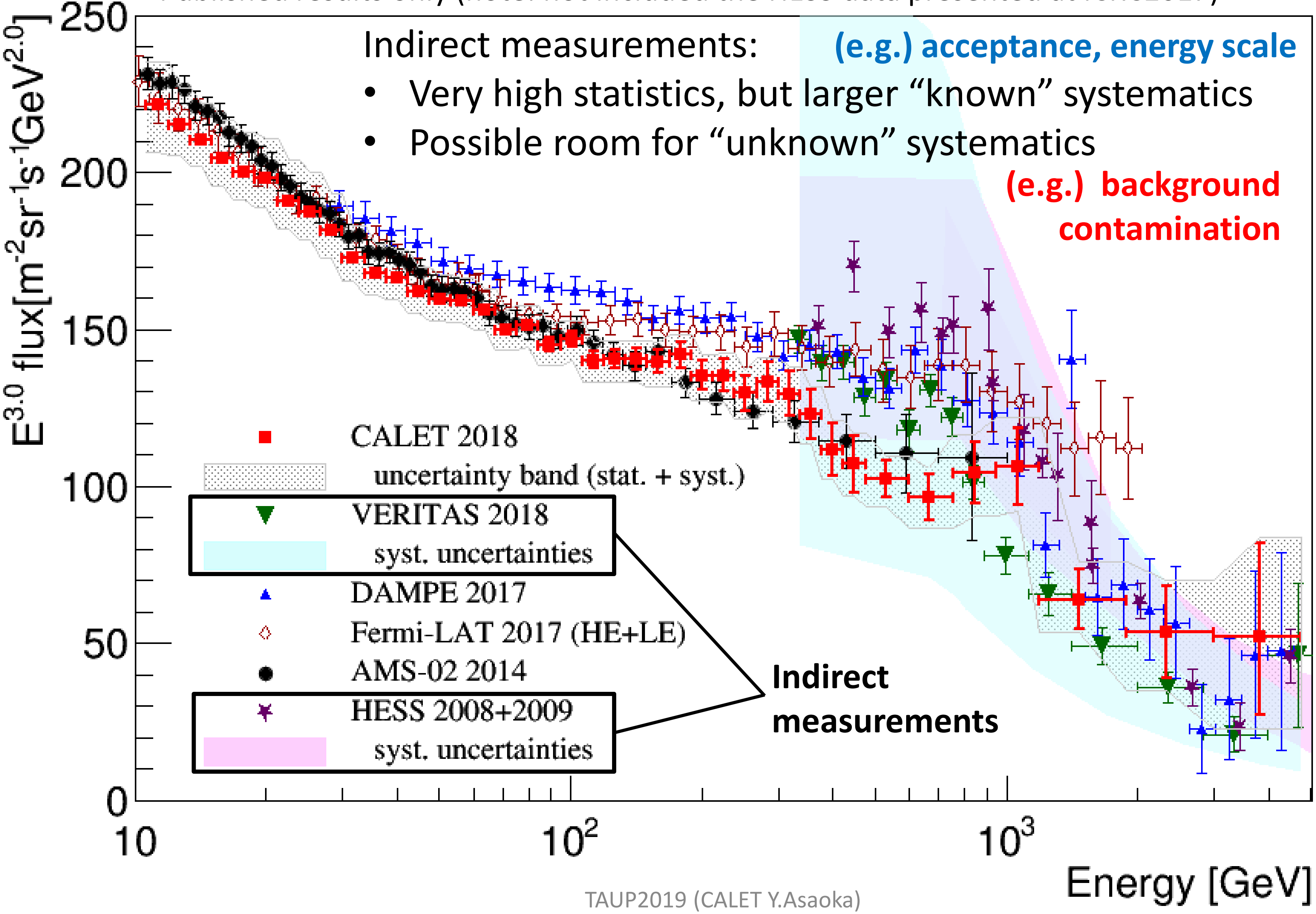
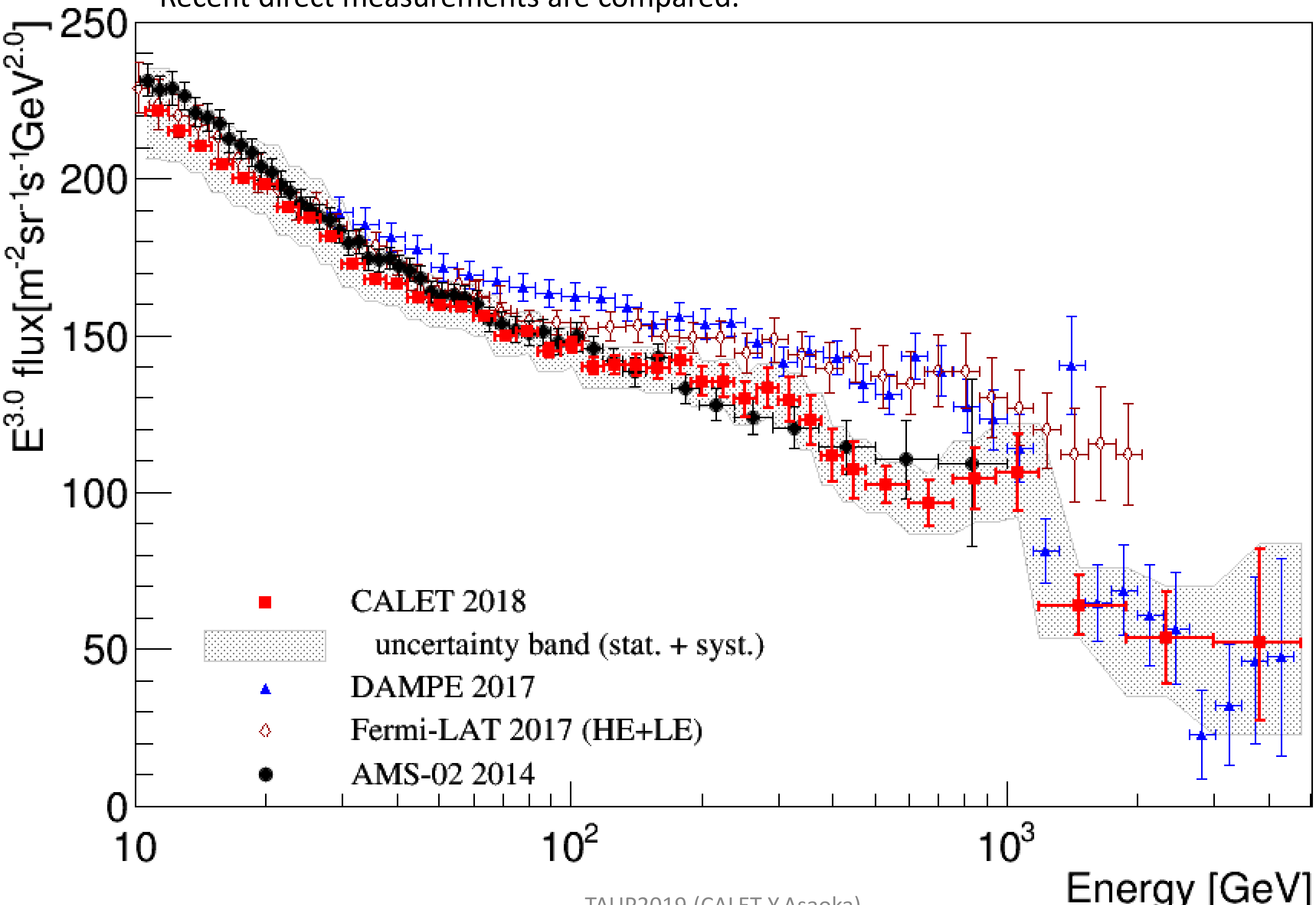


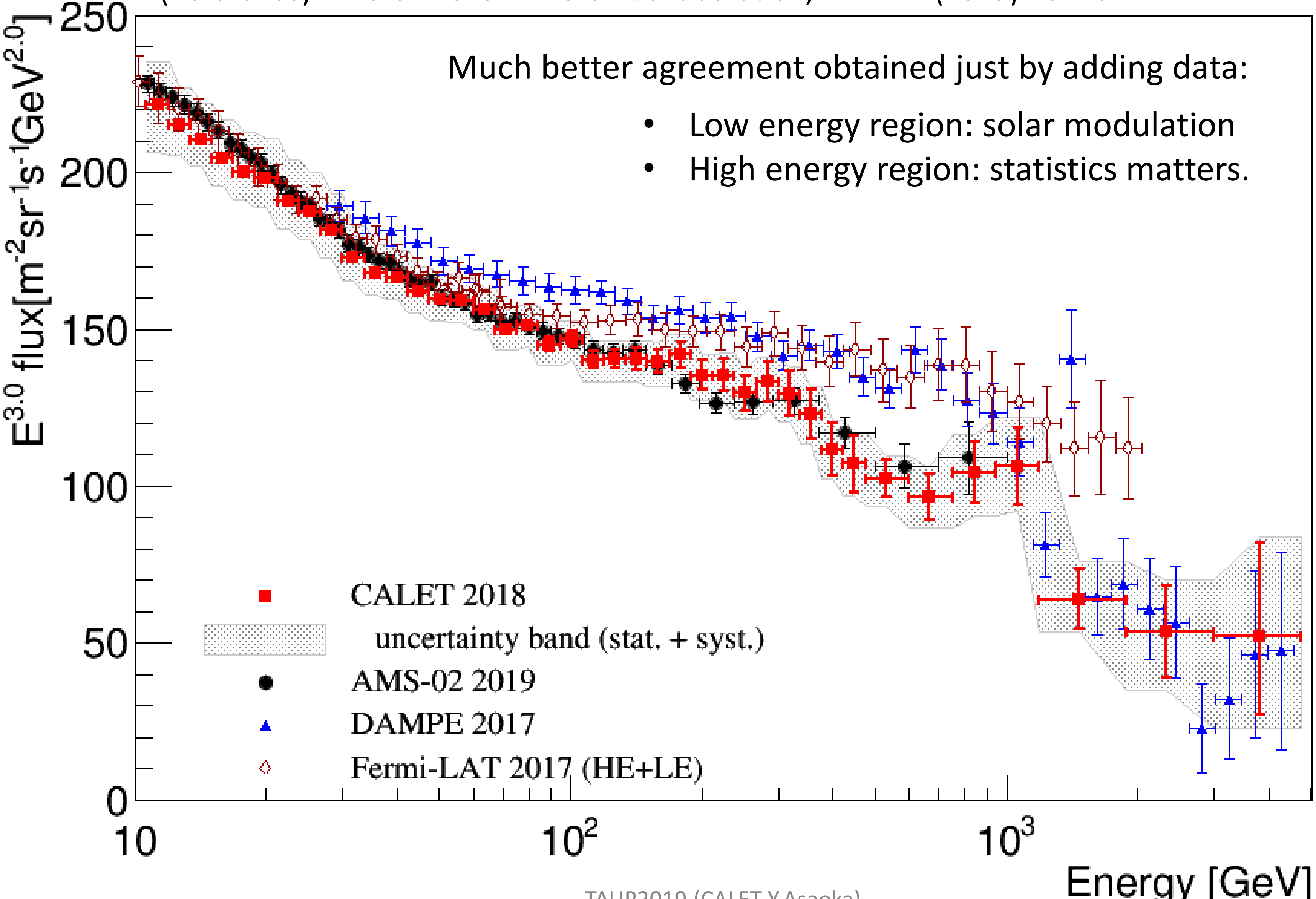
All Electron Spectrum: Comparison between Recent Direct Measurements

Recent direct measurements are compared.



All Electron Spectrum: Comparison with the Updated AMS-02 Result

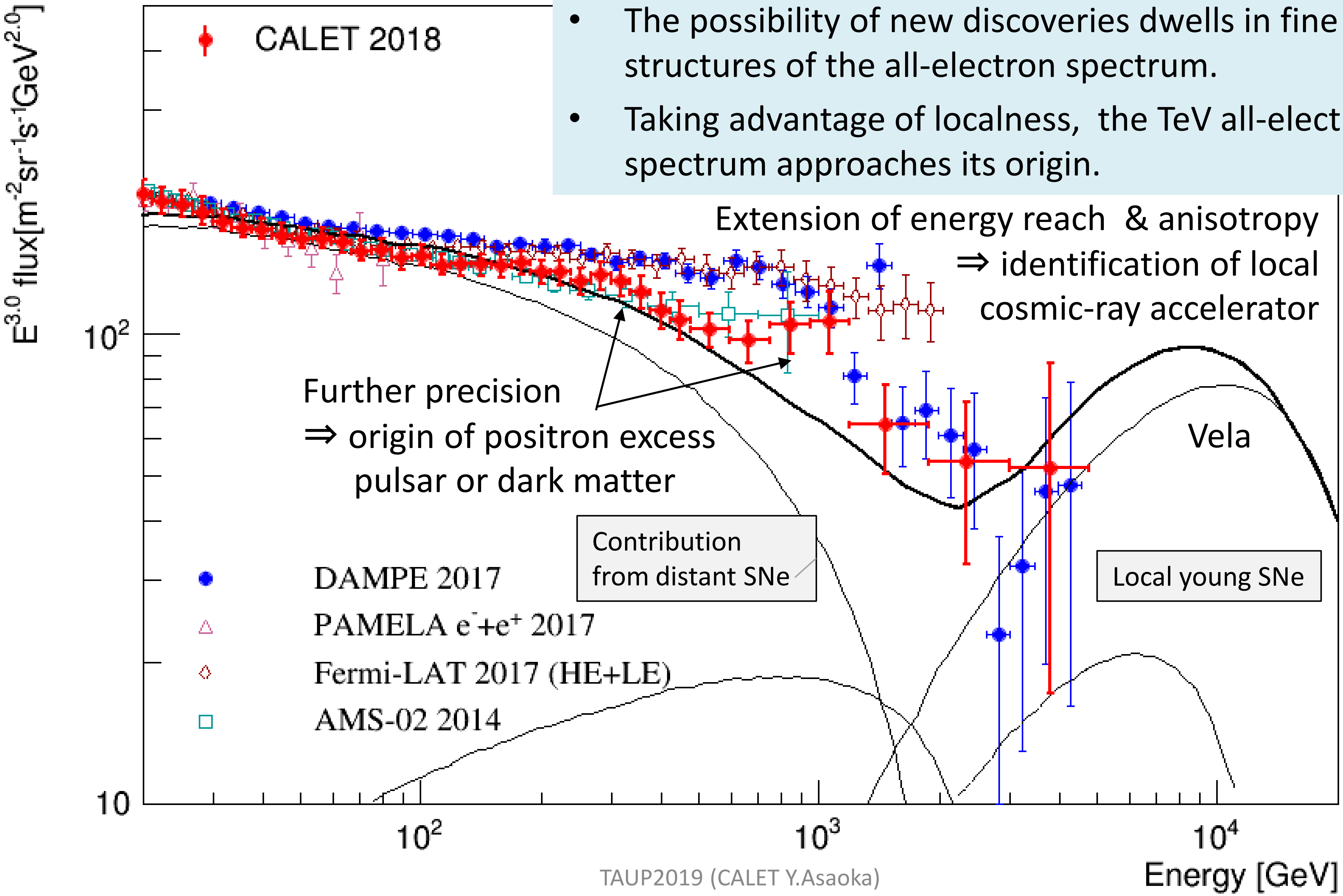
(Reference) AMS-02 2019: AMS-02 Collaboration, PRL 122 (2019) 101101



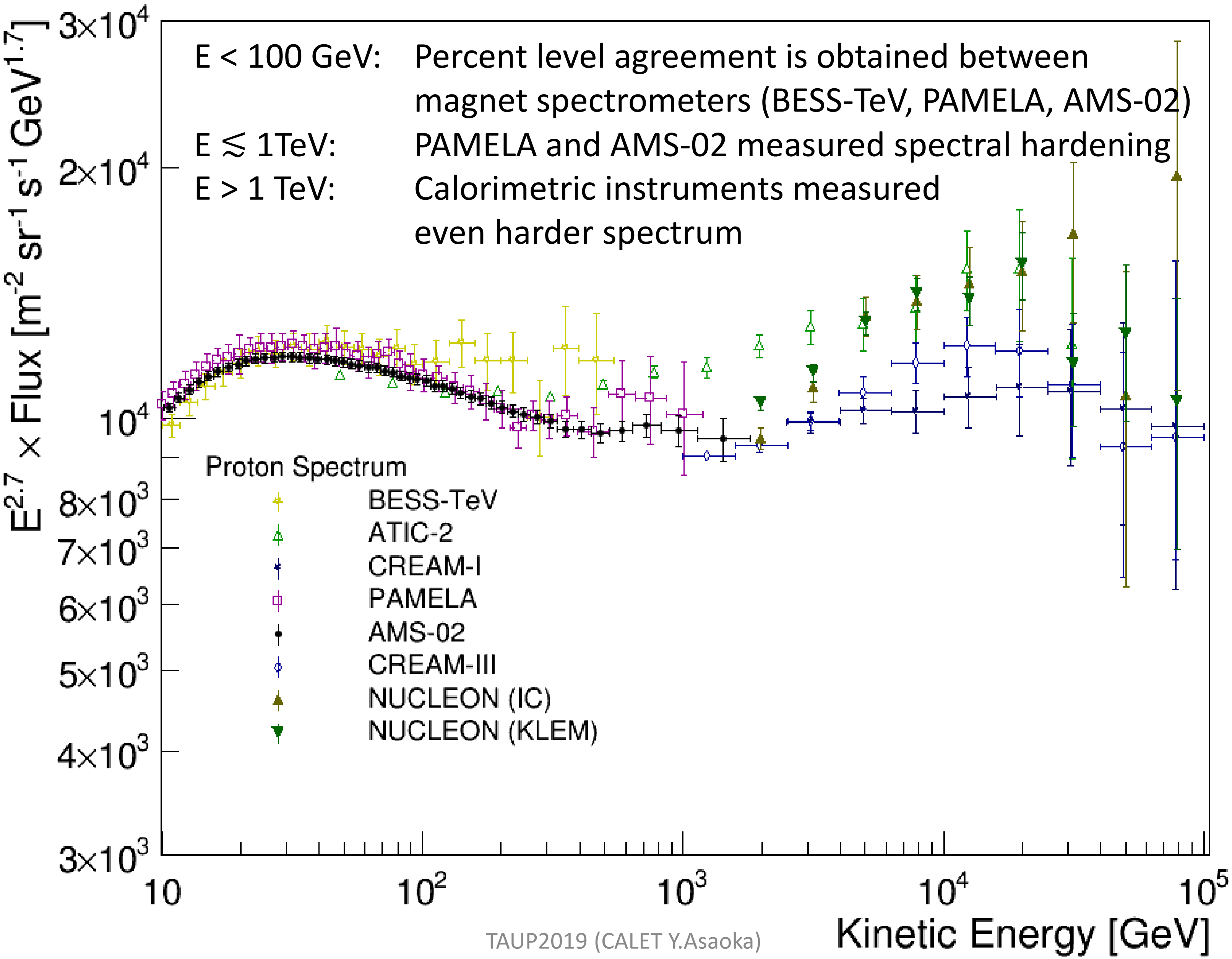
Prospects for the CALET All-Electron Spectrum

Five years or more observations ⇒ 3 times more statistics, reduction of systematic errors

- The possibility of new discoveries dwells in fine structures of the all-electron spectrum.
- Taking advantage of localness, the TeV all-electron spectrum approaches its origin.



Status of Cosmic-Ray Proton Spectrum Measurements



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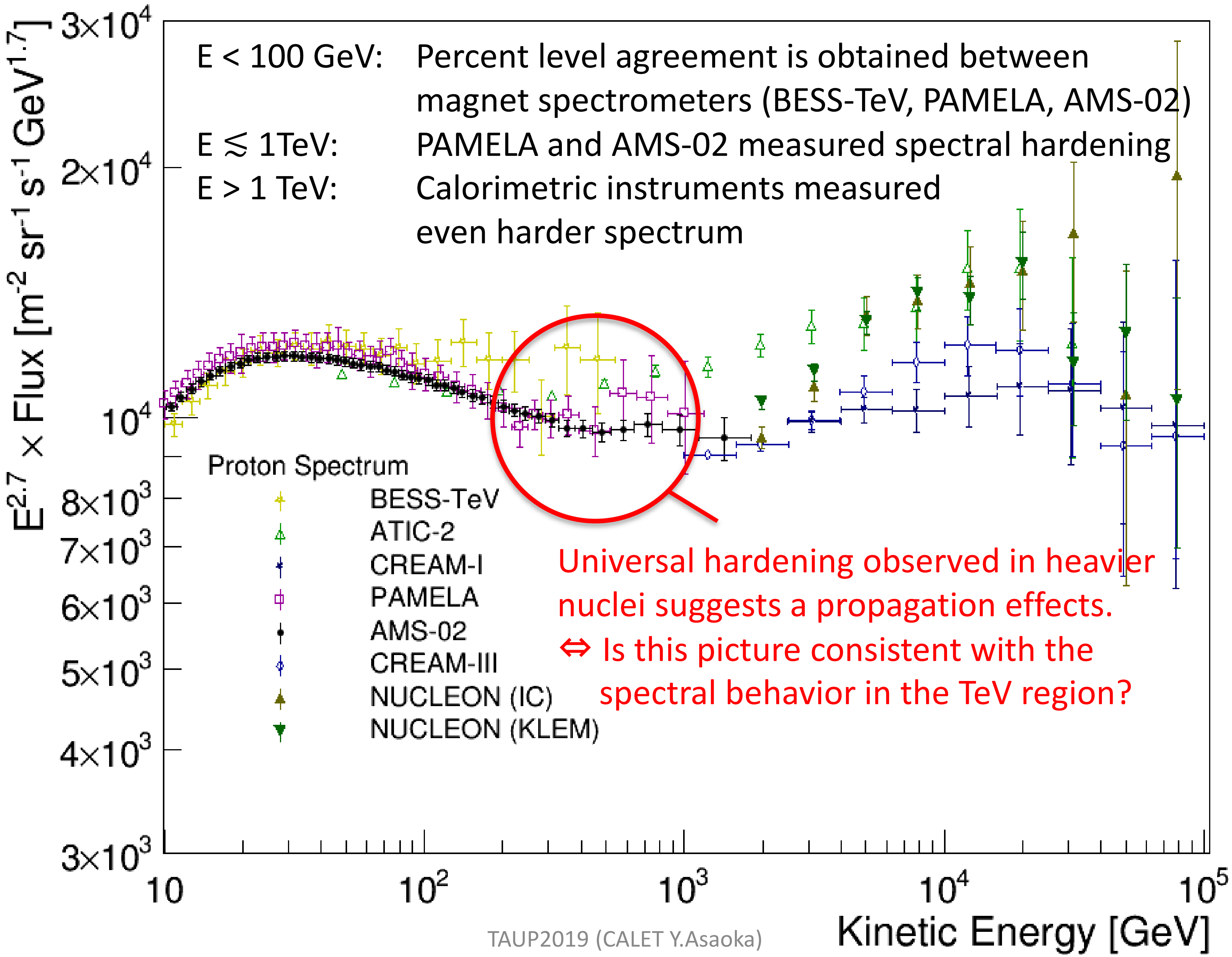

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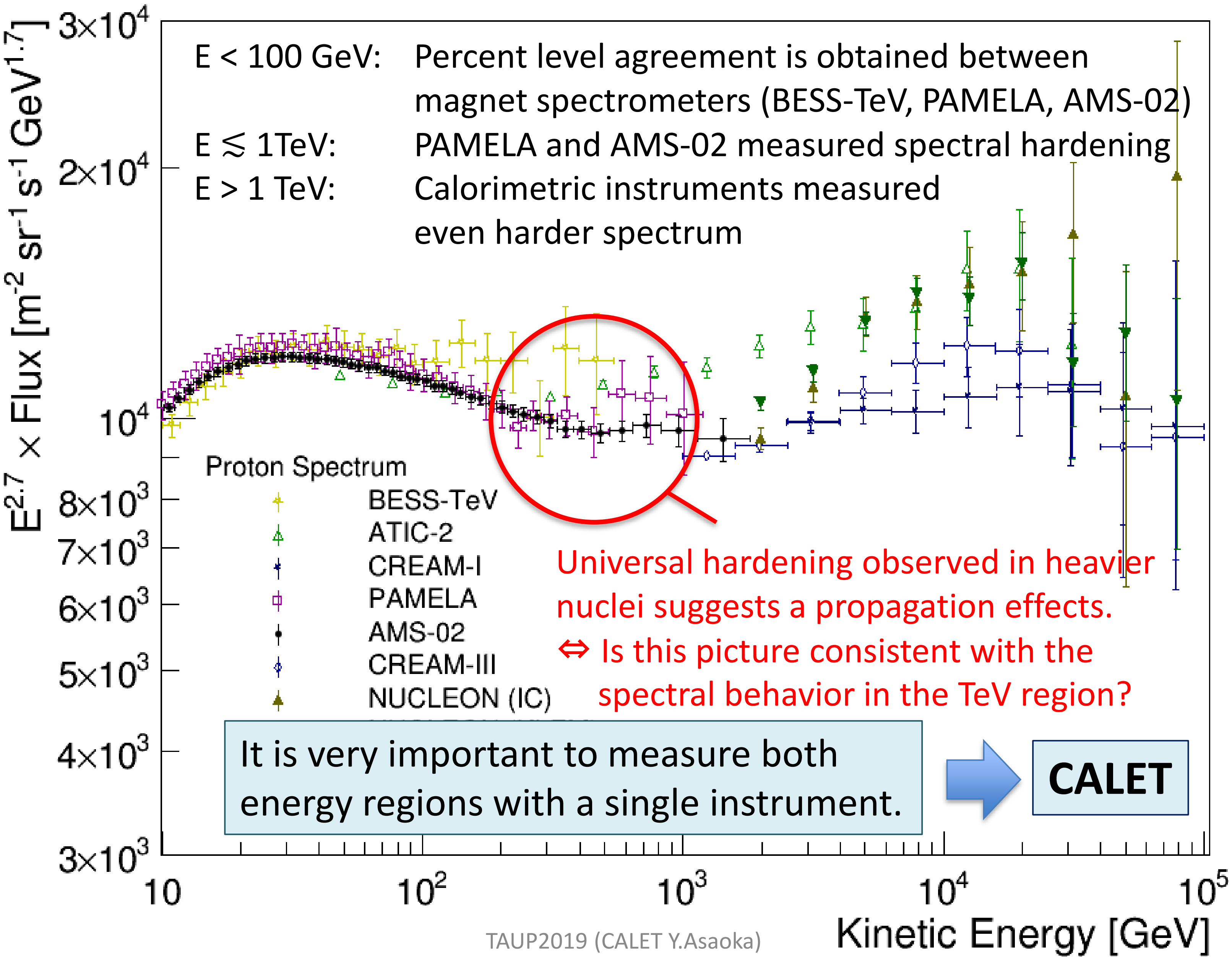


E < 100 GeV: Percent level agreement is obtained between magnet spectrometers (BESS-TeV, PAMELA, AMS-02)

E ≲ 1TeV: PAMELA and AMS-02 measured spectral hardening

E > 1 TeV: Calorimetric instruments measured even harder spectrum

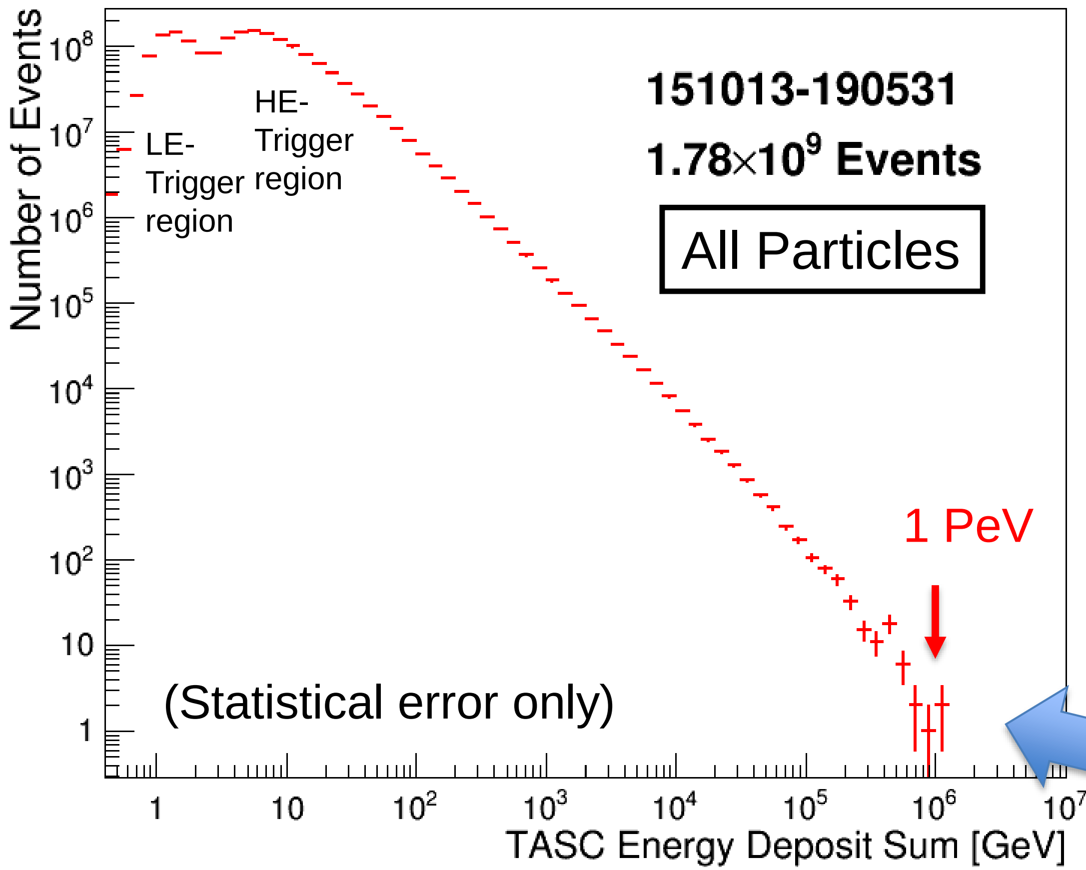
Universal hardening observed in heavier nuclei suggests a propagation effects.
⇔ Is this picture consistent with the spectral behavior in the TeV region?

It is very important to measure both energy regions with a single instrument.

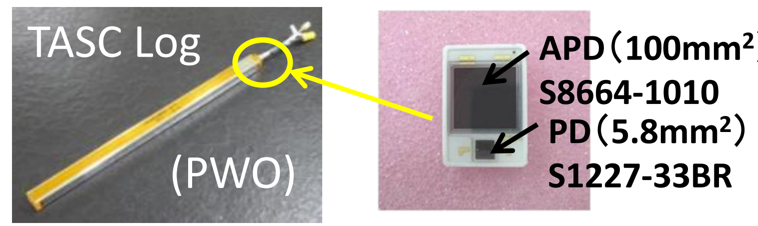
CALET

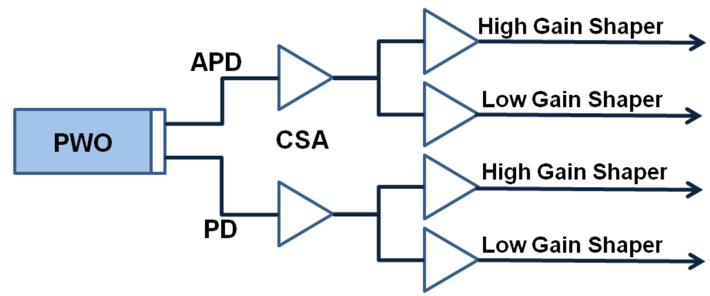
Wide Dynamic Range Energy Measurement

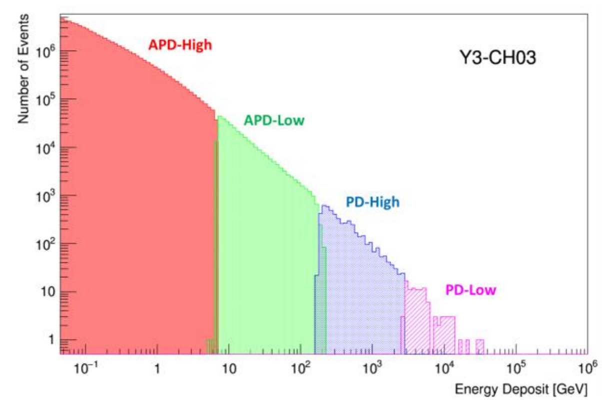
Distribution of TASC energy deposit sum



Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.





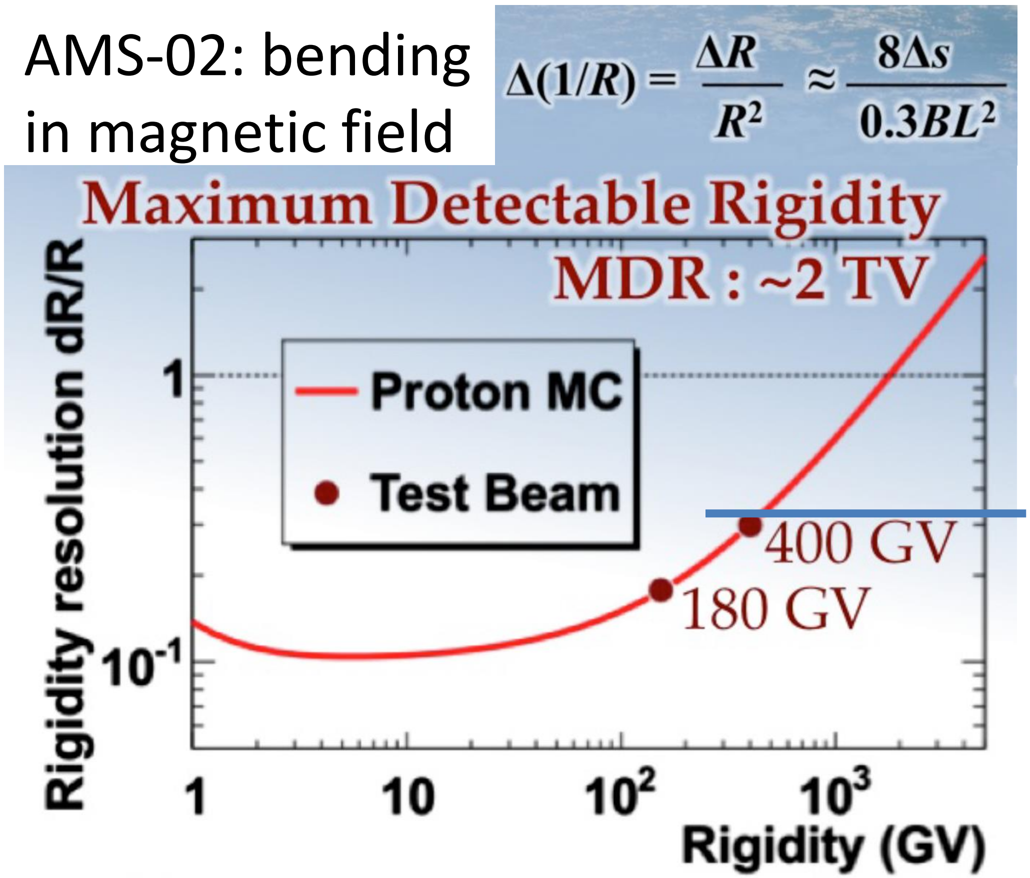


An example of gain connection in one PWO log:

The smooth distribution clearly reflects the power-law nature of cosmic-rays, demonstrating the reliability of the energy measurement over a wide energy range.

Energy Measurement of Protons: Magnetic Spectrometer vs Calorimeter

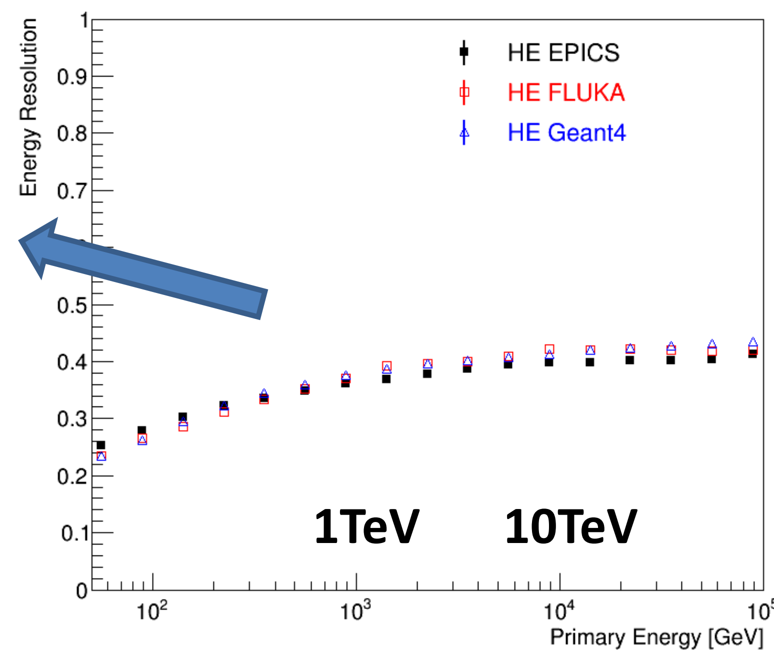
AMS-02: bending in magnetic field



Ref: Haino 2014

CALET: shower energy

Better resolution at E>500 GeV. Very stable above E>1TeV. Small dependence on MC models.



Proton Measurement with CALET: room for "unknown" systematics

1. Acceptance ⇒ **well defined SΩ**
   - Geometrical factor — **because of KF tracking and event selection**

2. Energy determination ⇒ **limited energy resolution but constant response, and confirmed by test beam**
   - Magnet Spectrometer
   - **Calorimeter**

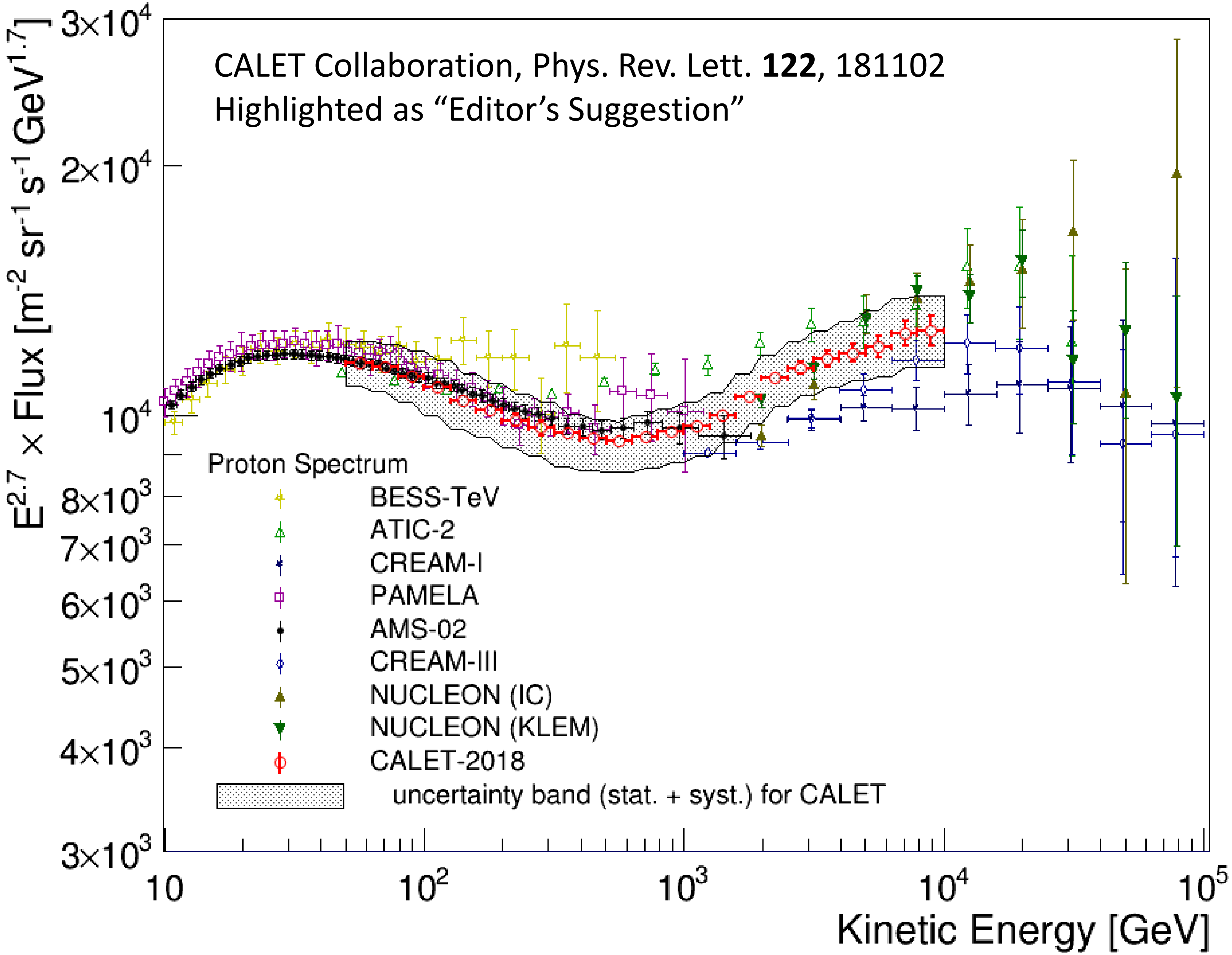
3. Particle identification ⇒ **excellent charge separation capability**
   - Contamination

4. Detection efficiency ⇒ **low efficiency, but confirmed by test beam**
   - Losses in the detector

⇒ **Needs special care for "unknown" systematics**

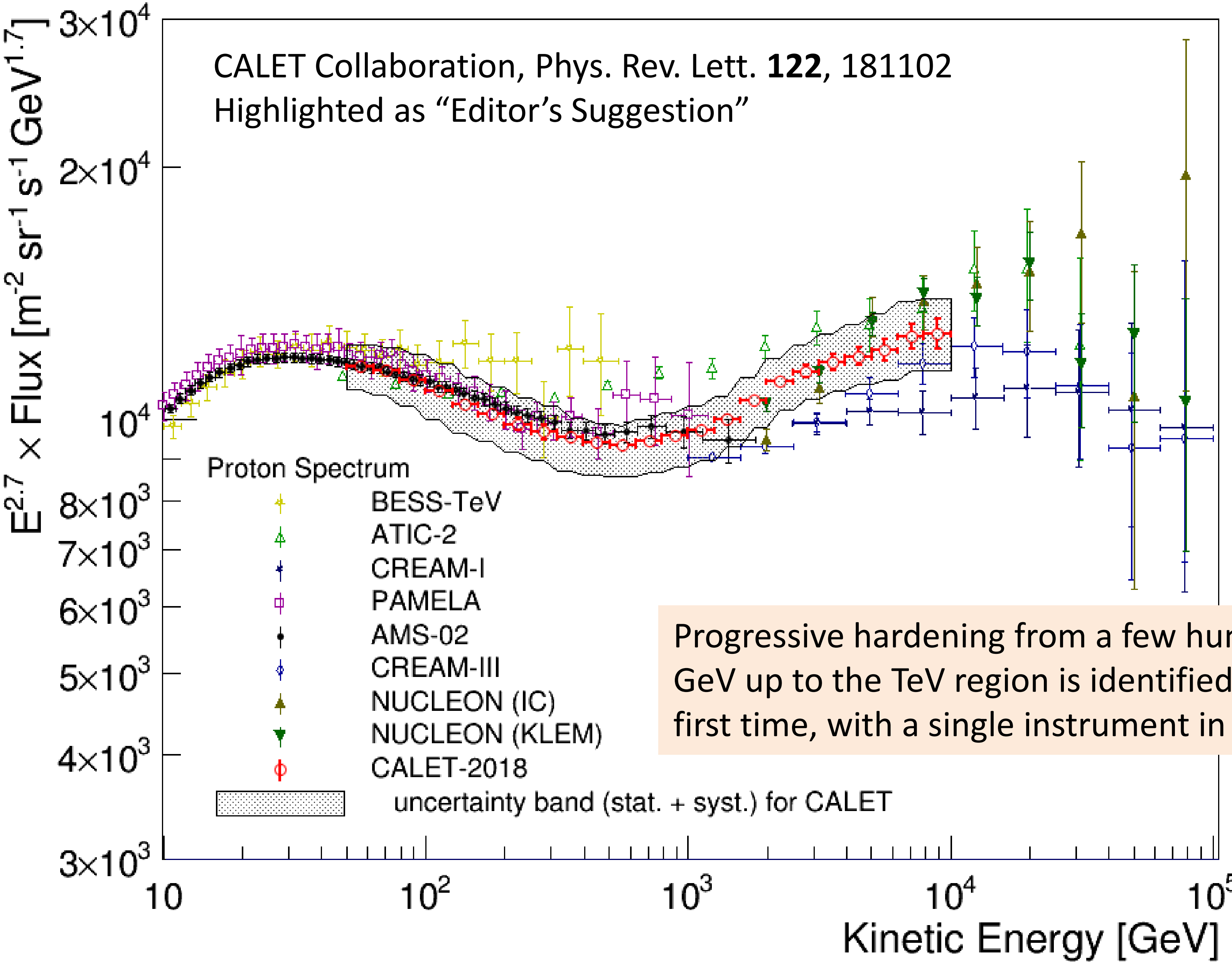
detailed systematic studies are carried out
(see the Supplement Material of PRL 122, 181102)

Cosmic-Ray Proton Spectrum from CALET



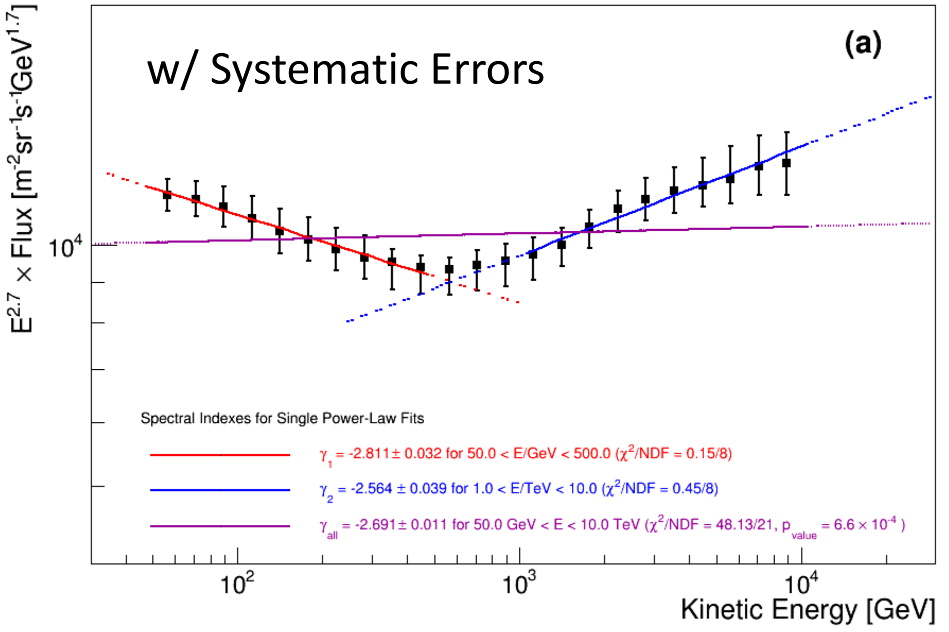
Cosmic-Ray Proton Spectrum from CALET

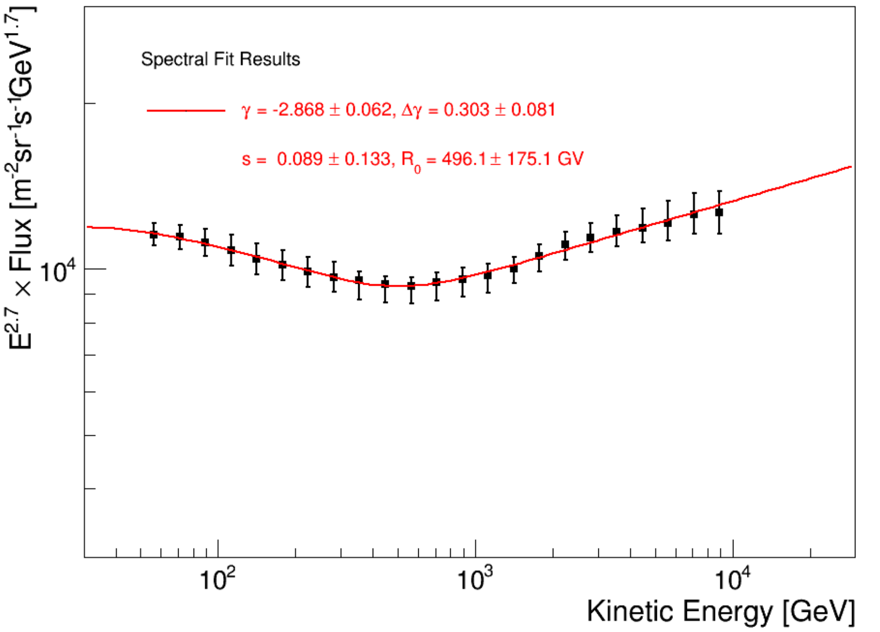
CALET Collaboration, Phys. Rev. Lett. **122**, 181102
Highlighted as "Editor's Suggestion"



Progressive hardening from a few hundred GeV up to the TeV region is identified, for the first time, with a single instrument in space

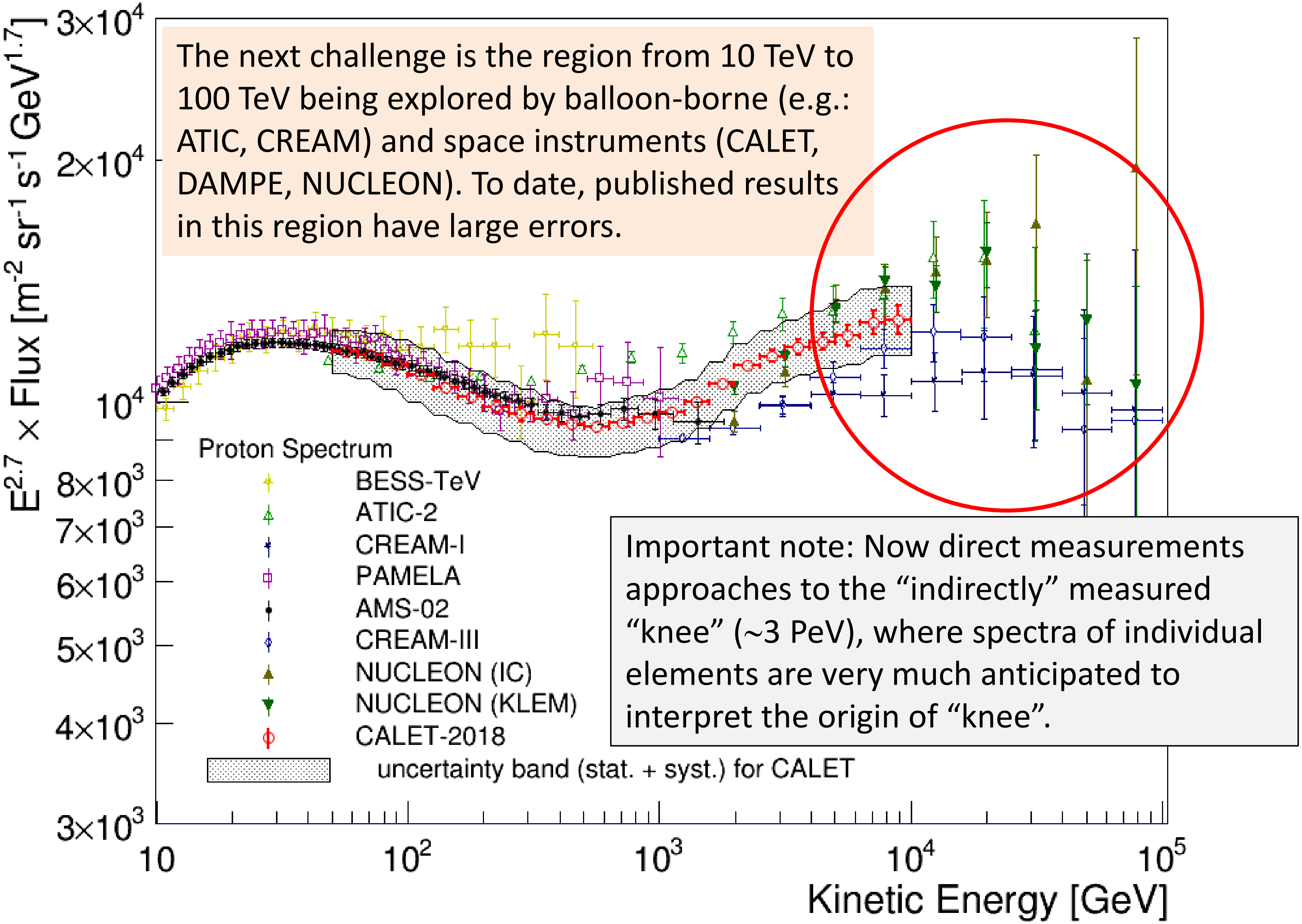
Spectral Behavior of Proton Flux





1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
2. Progressive hardening up to the TeV region was observed.
3. “smoothly broken power-law fit” gives power law index consistent with AMS-02 in the low energy region, but shows larger index change and higher break energy than AMS-02.

Prospects for the CALET Proton Spectrum

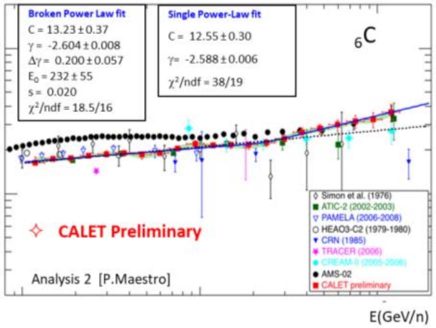


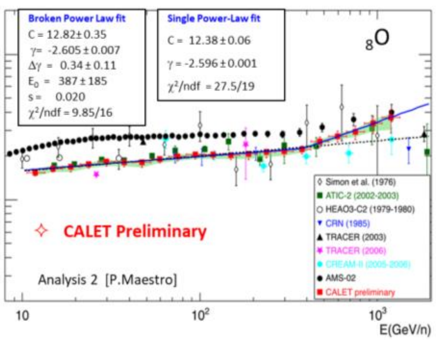
The next challenge is the region from 10 TeV to 100 TeV being explored by balloon-borne (e.g.: ATIC, CREAM) and space instruments (CALET, DAMPE, NUCLEON). To date, published results in this region have large errors.

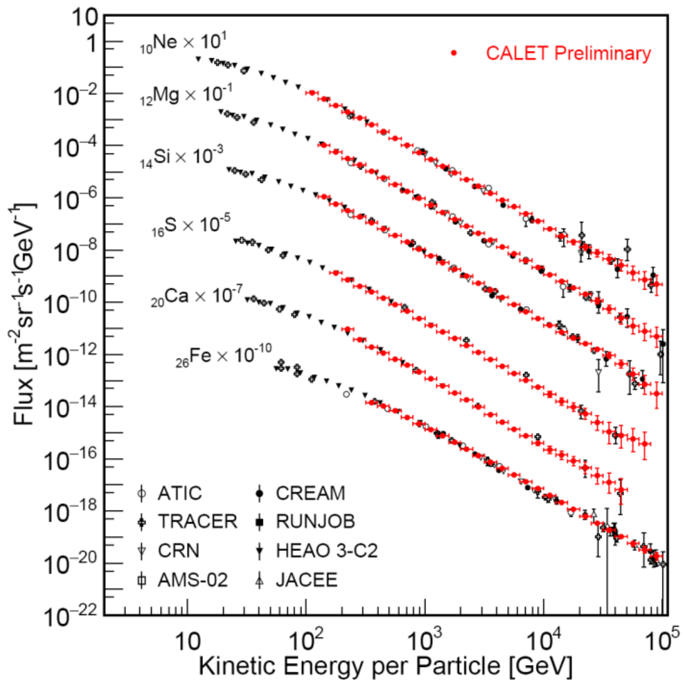
Important note: Now direct measurements approaches to the "indirectly" measured "knee" (~3 PeV), where spectra of individual elements are very much anticipated to interpret the origin of "knee".

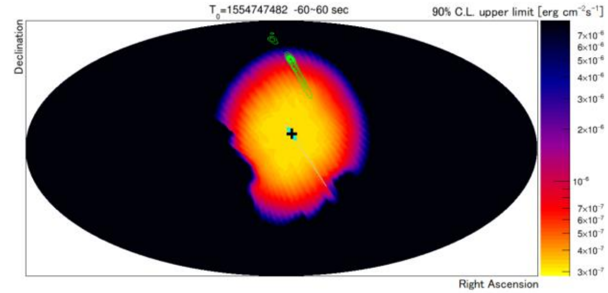
Summary and Prospects

- **CALET continues very stable observation since Oct. 2015, for more than 3.5 years.**
- **We have published all-electron spectrum (11 GeV – 4.8 TeV) and proton spectrum (50 GeV –10 TeV) including the detailed assessment of systematic errors.**
- **There are many more results such as heavy nuclei spectra, gamma-ray observations including GW counterpart searches, and space weather.**
- **The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year (or more) observation period is likely to provide a wealth of new interesting results.**









GCN No.	LIGO/Virgo trigger	Trigger time T_0 (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL α (°)	CAL δ (°)
24088	S190408an	04-08 18:18:02.288 UTC	0	2.3×10^{-6}†	80%	352.9	8.3
24218	S190425z	04-25 08:18:05.017 UTC	0	1.0×10^{-4}	5%	131.3	-43.6
24276	S190426c	04-26 15:21:55.337 UTC	0	2.5×10^{-5}	10%	183	-50.9
24403	S190503bf	05-03 18:54:04.294 UTC	0	4.2×10^{-5}	10%	169	-45.5
24495	S190510g	05-10 02:59:39.292 UT	0	–	No	295.7	50.8
24531	S190512at	05-12 18:07:14.422 UT	0	1.9×10^{-5}	10%	214.9	37.7
24548	S190513bm	05-13 20:54:28.747 UT	0	6.0×10^{-5}†	5%	348	4.4
24593	S190517h	05-17 05:51:01.831 UT	0	–	No	126.2	-31.9
24617	S190519bj	05-19 15:35:44.398 UT	0	–	No	243.1	51.1
24648	S190521g	05-21 03:02:29.447 UT	0	6.0×10^{-6}	30%	205.7	49.2
24649	S190521r	05-21 07:43:59.463 UT	0	–	No	225.3	51.4
24735	S190602aq	06-02 17:59:27.089 UT	0	2.9×10^{-4}	5%	127.5	45.1